

## Recent developments in dark matter physics

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**Abstract** : After a short review of the arguments for the existence of Particle Dark Matter in the Universe, I list the most plausible candidates provided by particle physics, *i.e.* neutrinos, axions, and WIMPs. In each case, I briefly describe how to estimate the relic density, and discuss attempts at detecting these particles. At the end, I discuss my personal favorite, the lightest supersymmetric particle, in a little more detail.

**Keywords** : Dark matter, axions, WIMPS

**PACS Nos.** : 14.80.Ly, 14.80.Mz

### 1. Introduction

Cosmological Dark Matter (DM) is stuff that at present only manifests itself through its gravitational interactions; in particular, it does not emit a detectable amount of electromagnetic radiation at any wavelength. Of course, the definition of "detectable" depends on the sensitivity of the instrument used for the search, which improves with time. Historically the first evidence for DM was found as early as 1845, when W.F. Bessel discovered irregularities in the proper motion of two stars, Sirius and Procyon [1]. He concluded that these stars must have "dark companions" of roughly their own mass. These companions were later found to be white dwarves, which at this relatively short distance are no longer "dark" by present standards.

This story of an early, successful DM search is encouraging. However, in modern understanding cosmological DM refers to stuff that is distributed over large distance scales, of the order of galactic radii or more ( $r \geq 20$  kpc;  $1 \text{ pc} = 3.24 \text{ lyr}$ ). This wider distribution makes detection of such kind of DM much more difficult than finding Bessel's "dark companions".

Evidence for the existence of galactic DM was found as early as 1922 by J H Jeans, who analyzed the motion of nearby stars transverse to the galactic plane [1]. He concluded that in our galactic neighborhood the average density of DM must be roughly equal to that

of luminous matter (stars, gas, dust). Remarkably enough, the most recent estimates, based on a detailed model of our galaxy, find quite similar results [2] : In particle physics units, the local DM density must be about

$$\rho_{\text{DM}}^{\text{local}} \simeq 0.3 \frac{\text{GeV}}{\text{cm}^3}; \quad (1)$$

this value is known to within a factor of two or so [2,3].

Currently the best evidence for galactic DM comes from the analysis of galactic rotation curves, *i.e.* measurements of the velocity with which things like globular clusters or gas clouds orbit around galaxies. For a stable circular orbit of radius  $r$  from the center of the galaxy, this velocity is given by

$$v(r) = \sqrt{\frac{G_N M(r)}{r}}, \quad (2)$$

where  $G_N$  is Newton's constant and  $M(r)$  is the total mass inside this orbit. If the mass of the galaxy was concentrated in its visible part, one would expect  $v(r) \propto 1/\sqrt{r}$  at large  $r$ . Instead, nearly all of the hundreds of rotation curves which have been studied so far, remain *flat* out to the largest observable values of  $r$ ; this implies  $M(r) \propto r$ , or  $\rho(r) \propto 1/r^2$ . One then concludes that galaxies contain more than ten times more dark matter than luminous matter. Mass densities averaged over the entire Universe are usually expressed in units of the critical or closure density,  $\Omega = \rho/\rho_c$  where  $\rho_c \simeq 10^{-29} \text{ g/cm}^3$ ;  $\Omega = 1$  then corresponds to a flat Universe. Galactic rotation curves imply

$$\Omega \geq 0.1; \quad (\text{galactic rotation curves}). \quad (3)$$

This is only a lower bound, since almost all rotation curves remain flat out to the largest values of  $r$  where one can still find objects orbiting galaxies; we do not know how much further the DM haloes of these galaxies extend.

There is considerable evidence for significantly larger  $\Omega$  from studies of larger structures, *e.g.* clusters or superclusters of galaxies. A fairly conservative observational lower bound on the total mass density of the Universe is

$$\Omega > 0.2 \text{ to } 0.3 \quad (\text{superclusters}). \quad (4)$$

Finally, to the best of my knowledge,  $\Omega = 1$  is compatible with all recent observations\*. This value is favored by "naturalness" arguments (since  $\Omega = 1$  remains constant in a Friedman-Robertson-Walker cosmology, while  $\Omega \neq 1$  implies an exponential time dependence of  $\Omega$ , making its present proximity to 1 difficult to understand), and is also predicted by most models of cosmological inflation. In contrast, the total luminous mass density only amounts to

$$\Omega_{\text{luminous}} < 0.01, \quad (5)$$

in clear conflict with the bounds (3) and (4).

\*Determination of supercluster masses based on X-ray temperatures gives lower values of  $\Omega$ . However, deriving the mass density from the measured X-ray energy spectrum is not straightforward, and this result seems to contradict more direct determinations based on gravitational lensing of galaxies lying behind these superclusters.

What could this Dark Matter be? We do not know the answer yet, but we do know that not all of it can be ordinary (baryonic) matter. This follows from analyses of Big Bang nucleosynthesis : Comparing the observed abundances of  $^2\text{H}$ ,  $^3\text{He}$  and  $^7\text{Li}$  with predictions, properly taking into account the chemical evolution of the Universe due to stellar "burning", one finds [4]

$$0.01 \leq \Omega_{\text{baryon}} h^2 \leq 0.015. \quad (6)$$

Here  $h$  is the Hubble constants in units of 100 km/(Mpc.sec). A conservative range for this quantity is  $0.4 \leq h \leq 0.9$ ; most recent measurements seem to cluster near the lower end of this range, between 0.45 and 0.65 or so [5]. The upper bound in (6) then implies  $\Omega_{\text{baryon}} < 0.1$ , in mild conflict with the constraint (3), and in sharp conflict with (4). This, in a nutshell, is the argument for the existence of exotic (non-baryonic)  $\text{DM}^\dagger$ . Note also that the lower bound in (6) is in conflict with the upper bound (5) on the amount of luminous matter, especially if the recent trend towards a small  $h$  holds up. In other words, there is considerable evidence for baryonic DM as well. The recent discovery of MACHOs [6] therefore confirms the validity of the overall picture, including the prediction of non-baryonic DM.

Finally, the important upper bound on the total mass density

$$\Omega h^2 \leq 1 \quad (7)$$

follows from the requirement that the Universe must be at least 10 billion years old, which is a conservative lower bound on the age of the oldest stars in our galaxy.

## 2. Candidates for particle dark matter

As discussed in the previous section, most of the mass of the Universe seems to be in the form of some exotic, non-baryonic matter. Fortunately particle physics offers a plethora of candidates for this dark matter. In this section I will briefly run through this list, focussing on those candidates whose original *raison d'être* has nothing to do with cosmological considerations.

### 2a. Light neutrinos :

Light neutrinos are the only particle DM candidates that are actually known to exist. As SM neutrino with mass  $m_\nu$  contributes [7]

$$\Omega_\nu h^2 = \frac{m_\nu}{90\text{eV}}. \quad (8)$$

Thus the  $\mu$  and/or  $\tau$  neutrinos could easily give  $\Omega_\nu \sim 1$  without violating laboratory constraints on their masses ( $m_{\nu_\mu} \leq 200 \text{ keV}$ ,  $m_{\nu_\tau} \leq 30 \text{ MeV}$  [8]). This appealingly simple solution of the DM problem suffers from two problems, however. First, the phase space density of neutrinos is limited by Fermi statistics. This makes it impossible for light

<sup>†</sup>The upper bound in (6) can be evaded if the baryons are stashed away in black holes prior to the onset of nucleosynthesis. However, it is not clear how a large population of such "primordial" black holes could have formed.

neutrinos to form the dark haloes of dwarf galaxies [9]. Secondly, light neutrinos are “hot” DM, meaning they were still relativistic when galaxy formation could have begun (when the causal horizon contained about 1 galactic mass). Hot DM has a large free-streaming length, which tends to smear out primordial density perturbations until neutrinos slow down sufficiently. As a result, models with (mostly) hot DM predict too few old galaxies [10], if quantum fluctuations are the “seed” of structure formation, as is assumed in inflationary models. However, in principle dark haloes of dwarf galaxies could be entirely baryonic without violating the nucleosynthesis constraint (6); and models where cosmic strings provide the seed of structure formation can accommodate hot DM [11]. Finally, it is worth pointing out that some Monte Carlo simulations of structure formation seeded by quantum fluctuations indicate [12] that the observed hierarchy of structures is reproduced best by a mix with  $\Omega_{\text{hot DM}} \simeq 0.25$ ,  $\Omega_{\text{cold DM}} \simeq 0.7$ , and  $\Omega_{\text{baryon}} \simeq 0.05$ .

Light neutrino DM also has the “practical” disadvantage that it is almost impossible to detect. By now these neutrinos are nonrelativistic, so their annihilation or scattering can only release a few (tens of) eV of energy. To my knowledge no scheme for their detection has yet been proposed. It is also almost inconceivable that the range of masses indicated by eq. (8) can be probed directly (kinematically) for the  $\mu$  and  $\tau$  neutrino. Our best hope is that massive neutrinos might mix with each other, leading to in principle observable neutrino flavor oscillations, which could allow us to determine the differences of their squared masses.

## 2b. WIMPs :

Weakly interacting massive particles (WIMPs) are particles with masses roughly between 10 GeV and a few TeV, and with cross sections of approximately weak strength. The reason for considering such particles as DM candidates rests on a curious “coincidence” : Their present relic density is approximately given by [3]

$$\Omega_{\text{WIMP}} h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle} \quad (9)$$

Here  $c$  is the speed of light,  $\sigma_A$  is the total annihilation cross section of a pair of WIMPs into SM particles,  $v$  is the relative velocity between the two WIMPs in their cms system, and  $\langle \dots \rangle$  denotes thermal averaging. This follows from the fact that WIMPs are non-relativistic already when they drop out of equilibrium with the hot thermal “soup” of SM particles (“freeze-out”), which occurs at temperature  $T_F \simeq m_{\text{WIMP}} / 20$  almost independently of the properties of the WIMP. One can then derive eq. (9) by requiring that the WIMP annihilation rate  $\Gamma = n_{\text{WIMP}} \langle \sigma_A v \rangle$  be equal to the expansion rate of the Universe  $H$  at  $T = T_F \simeq m_{\text{WIMP}} / 20$ <sup>#</sup>. Notice that the constant in eq. (9), 0.1 pb, contains factors of the Planck mass, the current temperature of the microwave background, etc.: it is therefore quite intriguing that it “happens” to come out near the typical size of weak interaction cross sections.

<sup>#</sup>In a more complete treatment the (logarithmic) dependence of  $T_F$  on  $\sigma_A$  has to be included, which leads to a set of coupled equations that can easily be solved by iteration [3].

Since WIMPs annihilate with very roughly weak interaction strength, it is natural to assume that their interaction with normal matter is also approximately of this strength. This raises the hope of detecting relic WIMPs directly [3], by observing their scattering off nuclei in a detector. The energy deposition can be several (tens of) keV. This is quite easily detected; however, care has to be taken to suppress backgrounds from ambient or intrinsic radioactivity, and from cosmic rays. There are now about 10 different groups searching for such signals [13].

Alternatively one can look for signals for ongoing WIMP annihilation. The WIMP density in free space is too small to give a detectable signal (except possibly near the center of our galaxy [3]). However, the same scattering processes that might allow to detect WIMPs directly can also lead to WIMP capture by celestial bodies, in particular the Earth or Sun. This happens if a WIMP loses so much energy in a scattering reaction that it becomes gravitationally bound. Eventually WIMPs will then become sufficiently concentrated near the center of these bodies to annihilate with significant rate. Once equilibrium is reached, the annihilation rate will simply be half the capture rate (half, since each annihilation event destroys two WIMPs). Since these annihilations occur near the center of the Earth or Sun, the only possibly detectable annihilation products are neutrinos, in particular muon (anti) neutrinos. The signal [3] is therefore muons pointing back towards the center of the Earth or Sun; the energy spectrum of these muons is also expected to be different from that produced by atmospheric (cosmic ray induced) neutrinos.

The perhaps most obvious WIMP candidate is a heavy neutrino. However, an  $SU(2)$  doublet neutrino will have too small a relic density if its mass exceeds a few GeV, as required by LEP data. One can suppress the annihilation cross section, and hence increase the relic density, by postulating mixing between a heavy  $SU(2)$  doublet and some “sterile”  $SU(2) \times U(1)_Y$  singlet neutrino. However, one also has to require the neutrino to be stable; it is not obvious why a massive neutrino should not be allowed to decay.

In supersymmetric models with exact R-parity the lightest supersymmetric particle (LSP) is absolutely stable. Searches for exotic isotopes [8] then imply that it has to be neutral. This leaves basically two candidates in the “visible sector”, a sneutrino and a neutralino. Sneutrinos again have quite large annihilation cross sections; their masses would have to exceed several hundred GeV for them to make good DM candidates. This is uncomfortably heavy for the lightest sparticle, in view of naturalness arguments<sup>§</sup>. Further, the negative outcome of various WIMP searches rules out sneutrinos as primary component of the DM halo of our galaxy [15]. In contrast, the lightest neutralino still can make a good DM candidate; this will be discussed in a little more detail in Section 3.

<sup>§</sup>In recently popular models with gauge-mediated SUSY breaking, the lightest “messenger sneutrino” could well be stable, and sufficiently massive, even though it is not the LSP [14]; note that most of its mass comes from supersymmetric terms, i.e. does not contribute to SUSY breaking.

### 2c. Axions :

Axions [16] are hypothetical pseudo-Goldstone bosons of a spontaneously broken new “Peccei-Quinn” (PQ) symmetry that allows to “rotate away” the CP-violating  $\theta$  parameter of QCD; in other words, axions have been introduced to solve the strong CP problem. They are not completely massless, since the PQ symmetry is not only broken by the vev of the scalar partner of the (pseudoscalar) axion, but also “explicitly” by nonperturbative QCD effects. As a result,

$$m_a \simeq 0.6 \text{ meV} \cdot \frac{10^{10} \text{ GeV}}{f_a}, \quad (10)$$

where  $f_a$  is the scale of PQ symmetry breaking and  $m_a$  is the mass of the axion. Relic axions are produced athermally during the QCD phase transition. If this is the main source of relic axions, then [17]

$$\Omega_a h^2 = 0.9 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{18} \cdot \overline{\theta_i^2}, \quad (11)$$

where  $\overline{\theta_i^2}$  is the average initial value of the axion field (written as a phase). This quantity is “naturally” of order unity, but it might be “accidentally” much smaller : in this case  $f_a$  would need to be correspondingly larger for axions to form significant amounts of DM. On the other hand, axion models often predict the existence of cosmic strings. In such scenarios the emission of axions from these strings is the main source of relic axions, and one would need a smaller  $f_a$  in order not to violate the bound (7). Finally, a series of laboratory and astrophysical constraints implies

$$f_a \geq 5 \cdot 10^9 \text{ GeV}. \quad (12)$$

In spite of their small mass, axions are cold DM, since they were produced athermally. They are much too light for the techniques used in WIMP searches to be applicable here. Instead, one looks for  $a \rightarrow \gamma$  conversion in a strong magnetic field. Such a conversion proceeds through the loop-induced  $a\gamma\gamma$  coupling, whose strength  $g_{a\gamma\gamma}$  is an important parameter of axion models. Currently two axion search experiments are taking data. They both employ high quality cavities, since the cavity “q-factor” enhances the conversion rate on resonance, i.e. if  $m_a c^2 = h\nu_{\text{res}}$ . One then needs to scan the resonance frequency in order to cover a significant range in  $m_a$  or, equivalently,  $f_a$ . The bigger of the two experiments, situated at the LLNL in California, started taking data in the first half of 1996. The analysis of the first data set, covering about 1/3 of a decade in  $m_a$  values, should be published soon [18].

The LLNL experiment uses “conventional” electronic amplifiers to enhance the conversion signal, albeit very sophisticated ones with exceedingly low noise temperature. In contrast, a smaller experiment now under way in Kyoto, Japan [19] uses Rydberg atoms (atoms excited to a very high state,  $n \simeq 230$ ) to detect the microwave photons that would result from axion conversion. In spite of the significantly smaller volume of this experiment, this allows them to reach better sensitivity than the LLNL experiment. While

the latter can only probe models where  $g_{a\gamma\gamma}$  is near the upper end of the expected range, the former will test all axion models that have been proposed to far. However, the tuning range, i.e. the range of  $m_a$  values that can be covered, is much smaller for the Kyoto experiment. This experiment started taking data at the very end of 1996, and should publish its results this year.

### 2d. Other candidates :

There are DM candidates which do not belong to any of the classes discussed so far. One example are new "baryons", which interact strongly with each other, but with gauge group different from the standard  $SU(3)_c$ . In analogy with the ordinary strong interactions, one usually assumes that these new "baryons" can annihilate into somewhat lighter, unstable new "mesons", with a cross section that more or less saturates unitarity limits [20]. Such "baryons" will have relic density  $\Omega \sim 1$  if their mass is  $O(500)$  TeV. "Baryons" with mass in this range could, e.g., exist [14] in the "hidden sector" of models with gauge-mediated SUSY breaking. Since these particles are singlets under the SM gauge group, their (loop-induced) interactions with ordinary matter are exceedingly feeble, making them almost impossible to detect experimentally. Similar candidates can also exist in extended technicolor models; however, these techni-baryons are more easily detected by WIMP search experiments [21].

Another possible DM candidate is the gravitino, the spin-3/2 superpartner of the graviton. This will usually be the LSP if the SUSY breaking scale\* is significantly below  $\sqrt{M_Z M_{Pl}} \sim 10^{10}$  GeV. Since gravitinos only interact gravitationally, they are still relativistic at freeze-out. However, the interaction strength of "longitudinal" ( $S_z = \pm 1/2$ ) gravitinos scales inversely proportional to the gravitino mass  $m_{\tilde{G}}$ . As a result, the relic density  $\Omega_{\tilde{G}} \propto m_{\tilde{G}}$ , and becomes  $O(1)$  for  $m_{\tilde{G}} \simeq 0.85$  keV [22]. Even though gravitinos are relativistic at freeze-out, by the time structure formation starts they have slowed down sufficiently to form "warm" DM, which resembles cold DM for most purposes. Finally, one could produce an additional "hot" (really, athermal) gravitino component from neutralino decays. While generating both (almost) hot and (almost) cold DM from the same particle looks like a neat trick, one needs slepton masses well in excess of 1 TeV for the "hot" component to be significant [22], which makes this scheme rather unattractive. Relic gravitinos are probably the most difficult to detect of all DM candidates.

### 3. The lightest neutralino

Let me now discuss my personal favorite DM candidate, the lightest neutralino, in a little more detail. It is my favorite since Supersymmetry is in my opinion the best motivated extension of the SM. When coupled with Grand Unification, SUSY models usually predict the lightest neutralino to be the lightest sparticle of the visible sector. While the possibility of having an even lighter "hidden sector" sparticle (like the gravitino) cannot a priori be

\*This scale is given by the expectation value of the largest SUSY-breaking  $F$  or  $D$  term; it should not be confused with the mass scale of ordinary sparticles, which for phenomenological reasons has to lie in the (few) hundred GeV to TeV range.

excluded, there is no good reason for such sparticles to be light enough to satisfy the bound (7) (e.g.,  $m_{\tilde{G}} < 1 \text{ keV}$ ; see Section 2c), given that the SUSY breaking scale is associated with the weak scale. Finally, while not easy to detect, there is hope that relic neutralinos can eventually be proven unambiguously (not) to exist.

The Minimal Supersymmetric Standard Model (MSSM) [23], to which I will restrict myself here, contains four neutralino current states: The superpartners of the  $U(1)_Y$  gauge boson (the “bino”  $\tilde{B}$ ), of the neutral  $SU(2)$  gauge boson (neutral “wino”  $\tilde{W}_3$ ), and of the two neutral Higgs bosons needed in any SUSY model [23] (“higgsinos”  $\tilde{h}_1^0$  and  $\tilde{h}_2^0$ , with  $Y_{\tilde{h}_1} = -Y_{\tilde{h}_2} = -1/2$ ). Since the electroweak gauge symmetry is broken, these current states mix to form four Majorana mass eigenstates. At tree-level the mass matrix in the basis  $(\tilde{B}, \tilde{W}_3, \tilde{h}_1^0, \tilde{h}_2^0)$  is given by

$$M_0 = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_w & M_Z \sin\beta \sin\theta_w \\ 0 & M_2 & M_Z \cos\beta \cos\theta_w & -M_Z \sin\beta \cos\theta_w \\ -M_Z \cos\beta \sin\theta_w & M_Z \cos\beta \cos\theta_w & 0 & -\mu \\ M_Z \sin\beta \sin\theta_w & -M_Z \sin\beta \cos\theta_w & -\mu & 0 \end{pmatrix} \quad (13)$$

Here,  $M_1$  and  $M_2$  are SUSY breaking gaugino masses,  $\mu$  is a supersymmetric Higgs (ino) mass parameter, and  $\tan\beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle$  is the ratio of vevs. The number of free parameters is reduced if one assumes that the gaugino masses unify, just like the MSSM gauge couplings seem to do [24]; this implies [23] for the running masses:

$$M_1 = \frac{5}{3} \tan^2 \theta_w M_2 \simeq 0.5 M_2, \quad (14)$$

where the second equality holds near the weak scale.

The size of the entries of the neutralino mass matrix (13) that mix gaugino and higgsino states is bounded by the mass of the  $Z$  boson. This is not surprising, since such mixing can only occur once  $SU(2) \times U(1)_Y$  is broken, and  $M_Z$  characterizes the strength of gauge symmetry breaking in the MSSM just as it does in the SM. On the other hand, the size of the diagonal entries  $M_1$ ,  $M_2$  and  $\mu$  is not (yet) known. It is useful to study two limiting situations, where  $|\mu|$  is either significantly larger or significantly smaller than the gaugino masses  $M_{1,2}$ .

In the first case,  $|\mu| > M_2$ , the lightest neutralino  $\tilde{\chi}_1^0$  is mostly a gaugino. If the unification relation (14) holds,  $\tilde{\chi}_1^0$  will be mostly a photino if  $M_2^2 \ll M_Z^2$ , turning into a bino if  $M_1 > M_2$ . The  $Z - \tilde{\chi}_1^0 - \tilde{\chi}_1^0$  coupling is then proportional to the square of the small higgsino component of  $\tilde{\chi}_1^0$  while the Higgs  $-\tilde{\chi}_1^0 - \tilde{\chi}_1^0$  couplings are linear in this small component. However, the  $\tilde{\chi}_1^0 - f - \bar{f}$  couplings have full  $[U(1)_Y \text{ or } U(1)_{em}]$  gauge strength. Unless  $m_{\tilde{\chi}_1^0} \simeq M_Z/2$  or  $m_{\tilde{\chi}_1^0} \simeq m_{\text{Higgs}}/2$ , in which case  $s$ -channel diagrams are “accidentally” enhanced, annihilation of these gaugino-like LSPs therefore proceeds dominantly through sfermion exchange in the  $t$ - or  $u$ -channel, leading to  $f\bar{f}$  final states. Since the cross section is proportional to the fourth power of the (hyper) charge, the dominant contribution comes from the exchange of (right-handed) charged sleptons. It has



been known for quite some time [25] that this leads to relic density  $\Omega_{\tilde{\chi}} h^2 \sim 1$  for very reasonable SUSY parameters. Specifically, for a bino-like LSP away from  $s$ -channel poles, one finds [26]

$$\Omega_{\tilde{\chi}} h^2 = \frac{\Sigma^2}{(1 \text{ TeV})^2 m_{\tilde{\chi}_1^0}^2} \cdot \frac{1}{\left(1 - m_{\tilde{\chi}_1^0}^2 / \Sigma\right)^2 + m_{\tilde{\chi}_1^0}^4 / \Sigma^2}, \quad (15)$$

where  $\Sigma = m_{\tilde{\chi}_1^0}^2 + m_{\tilde{t}_R}^2$ , and I have assumed three degenerate  $SU(2)$  singlet sleptons  $\tilde{l}_R$ . As advertised, this gives a cosmologically interesting relic density for sparticle masses in the (few) hundred GeV range.

This scenario is favored in models with GUT boundary conditions, if one assumes degeneracy of all soft breaking scalar masses at this very high energy scale. The electroweak gauge symmetry is then broken radiatively, and  $|\mu|$  usually comes out quite large [27], due to the large top mass. On the other hand, since the LSP couples only weakly to  $Z$  and Higgs bosons, its scattering cross section off ordinary matter is quite small. This illustrates that the "natural" assumption of a weak-scale scattering cross section, given a weak-scale annihilation cross section, can be off by a large factor. We saw that annihilation in this example proceeds through slepton exchange. However, slepton exchange can only contribute to LSP scattering off electrons, the cross section for which is suppressed by a factor  $(m_e/m_N)^2 < 10^{-6}$  compared to the one for scattering off nuclei. This latter process can proceed through squark exchange, but this entails a suppression factor  $(Y_{\tilde{q}} m_{\tilde{t}_R} / Y_{\tilde{t}_R} m_{\tilde{q}})^4$ , which can be as small as  $10^{-4}$  in many models. The dominant contribution to LSP scattering off nuclei therefore usually comes from scalar Higgs exchange, if the LSP is gaugino-like [3]. Since the relevant coupling is quite small, as discussed earlier, such relic LSPs are quite difficult to detect. For example, the direct detection rate in a Germanium detector is typically [28]  $10^{-4}$  to  $10^{-2}$  evts/(kg.day) for  $\mu < 0$ , and about five times larger for  $\mu > 0$ . This has to be compared with a current sensitivity which does not extend below  $10^{-1}$  evts/(kg.day); even next-generation experiments only aim for sensitivity around  $10^{-1}$  evts/(kg.day). However, reaching the necessary sensitivity is not inconceivable. Indirect detection (through LSP annihilation in the Earth or Sun) is also very challenging in this scenario.

In the opposite limit,  $M_1^2, M_2^2 \gg \mu^2$ , the lightest neutralino is dominantly a higgsino. Since the higgsino mass term  $\mu$  in eq. (13) connects  $\tilde{h}_1^0$  and  $\tilde{h}_2^0$ ,  $\tilde{\chi}_1^0$  is a combination of both current eigenstates

$$\tilde{\chi}_1^0 = \frac{1}{\sqrt{2}} (\tilde{h}_1^0 - \text{sign}(\mu) \tilde{h}_2^0) \quad (M_1^2, M_2^2 \rightarrow \infty) \quad (16)$$

Since the Higgs— $\tilde{\chi}_1^0 - \tilde{\chi}_1^0$  couplings probe both the higgsino and the gaugino components of  $\tilde{\chi}_1^0$ , these couplings again vanish in the limit (16). For finite  $M_1, M_2$ ,  $\tilde{\chi}_1^0$  is not exactly given by eq. (16); there are corrections of order  $M_W^2 / (\mu M_2)$ , hence the tree-level Higgs— $\tilde{\chi}_1^0 - \tilde{\chi}_1^0$  couplings will be of this order. Furthermore, the  $Z - \tilde{\chi}_1^0 - \tilde{\chi}_1^0$  coupling also vanishes in the limit (16), since it is [23] proportional to the difference of the squares of the

two higgsino components. Finally, the  $\tilde{\chi}_1^0 - f - \bar{f}$  couplings are now Yukawa couplings, and hence quite small except for  $f = t$  (and  $f = b$  or  $\tau$ , if  $\tan \beta \gg 1$ ). As a result, a higgsino-like LSP with mass  $m_{\tilde{\chi}_1^0} < M_W$  has a very small annihilation cross section, unless  $\tan \beta \gg 1$ .

One might therefore think that such a state has a very large relic density, see eq. (9). This is, however, not correct. The reason is that the MSSM contains three higgsino-like states if  $M_2^2 \gg \mu^2$ : The second lightest neutralino is a higgsino state orthogonal to the LSP (16), and the lightest chargino is also higgsino-like. All three states have mass  $|\mu|$ , up to corrections of order  $M_W^2 / M_2$ . For large  $M_2$  the mass splitting between these three states is therefore much smaller than the splitting between  $\tilde{\chi}_1^0$  and the (nearly) massless states of the SM. As a result, the three higgsino-like states remain in *relative* thermal equilibrium well after the entire SUSY sector has frozen out of equilibrium with the SM states. The reason is that reactions of the type  $f\tilde{\chi}_i^0 \leftrightarrow f\tilde{\chi}_j^0$  and  $f\tilde{\chi}_i^0 \leftrightarrow f'\tilde{\chi}_1^\pm$  occur much more frequently than reactions like  $\tilde{\chi}_i^0\tilde{\chi}_j^0 \leftrightarrow f\bar{f}$  if  $|m_{\tilde{\chi}_i} - m_{\tilde{\chi}_j}| \ll |m_{\tilde{\chi}_i} - m_f|$ .

Under such circumstances co-annihilation of the LSP with one of the heavier higgsinos becomes important [29]. That is, one also has to consider reactions like  $\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow f\bar{f}$  and  $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow f'\bar{f}'$  when estimating the relic density. Notice that the  $Z - \tilde{\chi}_1^0 - \tilde{\chi}_2^0$  and  $W^\pm - \tilde{\chi}_1^\pm - \tilde{\chi}_1^\pm$  couplings have full gauge strength in this scenario; the co-annihilation reactions therefore have quite large cross sections. As a result, the relic density of higgsino-like LSPs is actually quite small [30].

So far the analysis was based on tree-level results. Technically, the degeneracy of the three higgsino states in the limit  $M_2 \rightarrow \infty$  hinges on the fact that the  $\tilde{h}_1^0\tilde{h}_1^0$  and  $\tilde{h}_2^0\tilde{h}_2^0$  entries of the mass matrix (13) vanish; this is a consequence of  $SU(2) \times U(1)_Y$  gauge invariance. Since this gauge invariance is broken, we might expect such entries to be generated at the one-loop level. This is indeed the case [31], with the dominant contribution coming from heavy quark-squark loops [32]. In particular,  $t - \bar{t}$  loops generate a  $\tilde{h}_2^0\tilde{h}_2^0$  entry of order [32,33]

$$\delta_{44} = \frac{3G_F}{8\pi^2} \frac{m_t^2}{\sin^2 \beta} \sin(2\theta_{\tilde{t}}) \log \frac{m_{\tilde{t}_2}}{m_{\tilde{t}_1}} \quad (17)$$

where  $G_F$  is the Fermi constant,  $\tilde{t}_1$  and  $\tilde{t}_2$  are the two stop mass eigenstates, and  $\theta_{\tilde{t}}$  is the  $\tilde{t}_L - \tilde{t}_R$  mixing angle. Notice that the correction  $\delta_{44}$  vanishes if the two stop eigenstates are unmixed or degenerate in mass. Numerically,  $\delta_{44}$  can be as large as  $\sim 8$  GeV [33]. Note that  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq \delta_{44}$  and  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \simeq \delta_{44} / 2$  in the limit  $M_2 \rightarrow \infty$ . These mass splittings appear in the expression for the relic density due to co-annihilation in the form of exponential Boltzmann factors,  $\exp(-\Delta m_{\tilde{\chi}} / T_F) \simeq \exp(-20\Delta m_{\tilde{\chi}} / m_{\tilde{\chi}_1^0})$ . As a result, the loop corrections to the mass splittings can change the estimate of the LSP relic density by up to a factor of five in either direction, if  $\tilde{\chi}_1^0$  is a nearly pure higgsino state [33]. If the

sign of the correction is such that it increases the mass splittings, a state with 99.9% higgsino purity can form galactic DM ( $\Omega_{\tilde{\chi}} h^2 \geq 0.025$ ), while a state with 99.5% higgsino purity can form all cold DM in models with mixed cold and hot DM ( $\Omega_{\tilde{\chi}} h^2 \geq 0.15$ ).

Closely related  $t-\tilde{t}$  loop corrections can also have significant impact on the coupling of higgsino-like LSPs to Z and Higgs bosons, and thus on the expected LSP detection rate [33]. In particular, for  $\mu < 0$  the coupling to the lighter scalar Higgs boson can increase tenfold, which increases the estimate of the LSP detection rate by fully two orders of magnitude if this rate is dominated by scattering off spinless nuclei (e.g., direct detection using heavy nuclei, or capture in the Earth). The reason is that for this sign of  $\mu$  the tree-level coupling is not only suppressed by the small size of higgsino-gaugino mixing for  $M_{\tilde{t}}^2 \gg \mu^2$ , it also suffers additional "accidental" cancellations. Since the tree-level coupling is so small, loop corrections can even reverse its sign. As a result, the loop-corrected coupling, and the LSP scattering cross section off spinless nuclei, might vanish completely<sup>11</sup>. Fortunately the cross section for scattering off nuclei with non-vanishing spin remains finite in this case; it is, however, very small. Even for maximal positive correction, the LSP detection rate in a Germanium detector remains below  $10^{-2}$  evts/(kg.day) for  $\mu < 0$  and higgsino-like LSP; this is not much better than for bino-like LSP. However, for  $\mu > 0$  viable solutions can be found where the detection rate exceeds 0.1 evts/(kg.day); this necessitates a quite substantial gaugino component of the LSP (several percent at least).

Higgsino-like states with mass exceeding  $M_W$  again have quite small relic density, since they have large annihilation cross sections into  $W^+W^-$  and  $ZZ$  final states. Even in the absence of co-annihilation one needs  $m_{\tilde{\chi}_1^0} > 250$  (600) GeV for such an LSP to form galactic (all cold) DM. In this case the total co-annihilation cross sections are not much larger than the  $\tilde{\chi}_1^0 \tilde{\chi}_1^0$  annihilation cross section. Nevertheless co-annihilation will increase these lower bounds, possibly by as much as a factor of two.

Finally, if the unification condition (14) does not hold, the LSP might also be  $\tilde{W}_3$ -like. This again leads to a tiny relic density [34]. The culprit is again co-annihilation, this time exclusively with the nearly degenerate lighter chargino. The tree-level mass splitting in this case is even smaller than that between the higgsino-like states, and loop corrections only amount to less than 100 MeV here. Furthermore, the  $W^\pm - \tilde{\chi}_1^0 - \tilde{\chi}^\pm$  coupling is now a triplet coupling, rather than a doublet coupling as in case of higgsino-like LSP. As a result, the relic density  $\Omega_{\tilde{\chi}} h^2$  is below  $10^{-4}$  for  $m_{\tilde{\chi}_1^0} \leq M_W$ . A neutral wino-like LSP is therefore definitely not a good DM candidate.

<sup>11</sup>The zero of the scattering matrix element occurs for slightly different parameter combinations than the zero of the  $\tilde{\chi}_1^0 - \tilde{\chi}_1^0 - h^0$  coupling, since the matrix element also gets contributions from heavy Higgs and squark exchange [3].

#### 4. Summary and conclusions

There are compelling arguments for the existence of exotic dark matter in the Universe. We don't presently know just what this DM is made of, but there are many particle physics candidates standing in line to fill this vacancy. Out of these the best motivated ones are light neutrinos, axions and neutralinos.

Light neutrinos are known to exist, but it is not clear whether they have the required mass, in the range of a few (tens of) eV. Unfortunately testing whether relic neutrinos form all or part of the required DM is exceedingly difficult, due to the minuscule size of the relevant cross sections and the small amount of the energy that could possibly be deposited by them. In case of  $\mu$  and  $\tau$  neutrinos a direct kinematical measurement of eV scale masses using lab experiments is also essentially hopeless. Such experiments might teach us something about differences of squares of neutrino masses, *if* the different neutrino flavor eigenstates mix sufficiently strongly. However, the only reasonably direct way of measuring eV scale  $\nu_\mu$  and  $\nu_\tau$  masses that I can think of is through precise timing of neutrino pulses emitted by supernovae; unfortunately we may have to wait decades for the next sufficiently close explosion. Finally, recall that current conventional wisdom disfavors neutrinos as dominant DM component.

Axions have been postulated in order to solve the strong CP problem. In my view they suffer from the theoretical, or rather aesthetical, problem that this explanation does not constrain the scale  $f_a$  at all; in principle it could be anywhere between  $\Lambda_{\text{QCD}}$  and  $M_{\text{Pl}}$ . Laboratory searches and astrophysical constraints exclude the lower half of this range (on a logarithmic scale), while the bound [7] on the relic density excludes, or at least strongly disfavors, very large values of  $f_a$ . At present one or two decades in between are still allowed. This can be interpreted in two ways. If you don't like axions, you might argue that they suffer a finetuning problem, since most of the a priori allowed range is already excluded. If you do like axions, you can emphasize the fact that in this allowed window, axions probably form at least a significant fraction of all DM. In any case, axions are quite unique in particle physics in that relic axions are the *only* axions that we can possibly detect. Indeed, we'll probably know within a decade or so whether axions form a significant of the dark halo of our own galaxy.

However, other solutions of the strong CP problem have been suggested. In fact, some people [35] (including myself) consider this problem to "only" be one aspect of the overall flavor problem, so introducing a special particle just for this one facet of the problem seems rather extravagant. In contrast, Supersymmetry is the so far only solution of the hierarchy problem that is at least potentially fully realistic (in agreement with all existing data). Moreover, in the simplest viable models the lightest neutralino emerges almost automatically as an attractive DM candidate. The *only* assumption one has to make is that of minimality—that is, that certain couplings, which seem entirely unnecessary, are indeed absent in the Lagrangian, so that R-parity is conserved.

We saw in Section 3 that in general the lightest neutralino can come in different forms. A photino- or bino-like state makes the most natural DM candidate in the sense that it has a cosmologically interesting relic density for a fairly wide region of parameter space. A smaller window exists also for a light higgsino-like LSP, partly due to radiative corrections which can be quite important in this case. Such relic neutralinos are probably quite difficult to detect, although the task is at least not as hopeless as for certain other DM candidates discussed in Section 2d. Fortunately sparticles should leave plenty of tell-tale signatures in collider experiments. In particular, the forthcoming LHC at CERN should be able to unambiguously test the idea of weak-scale Supersymmetry [36]. However, even if SUSY is first discovered at colliders, relic LSP searches do not become less important. For one thing, their mere detection would immediately raise the lower bound on their lifetime from something like  $10^{-7}$  seconds, which is an optimistic guess for the sensitivity of collider experiments, to about  $10^{+18}$  years, an improvement of some 32 orders of magnitude! Even more exciting detecting relic neutralinos, or any other kind of exotic dark matter, would finally tell us what gives the Universe (most of) its mass.

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